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Energy security and co-benefits of energy efficiency improvement in three Asian countries

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ABSTRACT

Energy and energy security have become important to countries aiming to go on the path of sustainable development. In this regard this paper analyses the improvement of energy security which occurs as a result of energy efficiency (EE) improvements in the power sector. In this paper energy security is measured along three main themes which are oil security, gas security and sustainability. The energy systems of the selected countries, namely Sri Lanka, Thailand and Vietnam are modeled using an integer programming based optimization model called “Model for Energy Supply Strategy Alternatives and their General Environmental Impacts” – MESSAGE. Each country is modeled with two scenarios namely the reference scenario which maintains the status quo at the start year and the EE scenario which models EE options in the demand side as supply side alternatives. The time horizon is 2007–2030, where 2007 is the base year and 2030 is the end year. The results are presented for oil security, gas security, sustainability, and also for co-benefits such as mitigation of CO_2 emissions, reduction in conventional primary energy use and reduction of local air pollutants such as SO_2 and NO_x. Results show that energy efficiency in Sri Lanka significantly increases the energy security whilst also accruing co-benefits of CO_2 mitigation, mitigation of local air pollution and reducing the conventional primary energy use. In the case of Thailand and Vietnam, energy security is enhanced in the earlier years (2007–2015), but in the longer term of modeling horizon (2020–2030) energy security of both the reference and EE scenarios converge indicating that in terms of long term energy security implementing energy efficiency measures alone would not enhance energy security.

Contents

Abbreviations: CECap, carbon emission per capita; CEInt, carbon emission intensity; DOFS, diversity of fuel share; EE, energy efficiency; GI, gas intensity; GII, gas import intensity; GMS, greater mekong sub-region; GS, gas share; GSRI, gas supply risk indicator; IAEA, International Atomic Energy Agency; IIASA, International Institute of Applied Systems Analysis; MESSAGE, model for energy supply strategy alternatives and their general environmental impacts; NCFS, non-carbon fuel share; NG, natural gas; NGID, net gas import intensity; NOID, net oil import intensity; OI, oil intensity; OII, oil import intensity; OS, oil share; OSRI, oil supply risk indicator; PG, power generation; RFS, renewable fuel share; TPES, total primary energy supply

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1. Introduction

Energy security has permeated into the energy lexicon of 21st century, and has gained much prominence [1]. Even though researchers conclude that there is no definitive explanation that can be given for the term 'energy security', the consensus is that energy security means varied things to various countries, and energy systems [2].

Many supra national institutions and developmental agencies have authored a multitude of research works on energy security. Reference [3] indicates that energy security is the "constant availability of affordable energy supplies" whilst [4] defines energy security as the "ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner, with the energy price being at a level that will not adversely affect the economic performance of the economy". The former definition, whilst being succinct and its interpretation more suited to the layman, simplifies the context of energy security and the latter definition is more in-depth and covers the multiple context of energy security whilst connecting energy to the economy of the nation state or region.

The modern school of thought on energy security has proclaimed that energy security needs to be viewed holistically [5]. References [5–7] have mentioned the different themes which encompass the meaning of energy security in the modern day energy regime.

In terms of measurement and assessment of energy security, Ref. [8] presents the summarized review of the indicators and indices present for measuring energy security. Refs. [4,9–11] provide composite indicators for measuring energy security, oil security, gas security and vulnerability of energy systems respectively. But as mentioned before, these indicators are one-dimensional in nature, as they only account for one facet of energy security. The sustainability aspect of energy security is deemed to be of utmost importance by [12,13] and more so for developing countries. In view of that, this research study contends that the sustainability theme of energy security is also vital to assessing energy security. This presumption is well backed by [14]. Some indicators proposed to measure sustainability of an energy system are given in Refs. [15,16]. As per the review presented before, this research article will assess energy security along three main themes which are oil security, gas security and sustainability.

Another important aspect of energy security research is that the means of achieving energy security is very much temporal and contextual in nature. By this, the implication is that depending on the nature of energy-economy system the focus of energy security should shift. In a groundbreaking report published by [17], it is stated that the most effective way of achieving energy security is by focusing on energy efficiency. This report also identifies energy efficiency as an effective way of ensuring the energy security of developing countries. In addition to this report countless other reports of agencies like [18–20] also point out the importance of energy efficiency to improve energy security of developing countries. Energy efficiency in the power sector is dealt with in Integrated Resource Planning (IRP), where the energy efficiency measures are taken into the planning framework as supply side options [21].

The comprehensive review of energy security, energy security indicators and related topics are given in Table 1. Energy security in the reviewed papers has been treated exhaustively. With the advent of increase of popularity of energy security, most papers carried explorative studies of energy security. When the understanding of energy security had permeated into mainstream conscience, more quantitative discussions are currently taking place.

All this goes onto point the impetus energy analysts and policymakers place on the need of a country to be energy secure and validates the premise that assessing the impact of any energy policy measure on the energy security of a country is the need of the hour.

The objective of this research paper is to formulate an assessment framework of energy security, where energy security is measured as oil security, gas security and sustainability and measure the energy security and co-benefits ensuing as a result of energy efficiency measures in three developing Asian countries, namely Sri Lanka, Thailand and Vietnam. The co-benefits analyzed in this paper are CO_2 mitigation, air pollution reduction and the reduction in primary conventional energy use. Rather than focusing on the ways to implement and achieve energy efficiency in the power sector, this paper focuses on the effect of energy efficiency measures on energy security of developing countries. Three developing countries in Asia that have been chosen are Sri Lanka, Thailand and Vietnam. Sri Lanka is an island nation in the Indian Ocean, with an approximated population of 21 million people. In terms of its energy use, it is predominantly traditional biomass based, with an electrification rate of approximately 70% [31]. Sri Lanka does not have a well documented energy system. The present government came up with an energy policy paper [32] which gives direction to energy policy of Sri Lanka. Thailand is a Southeast Asian nation with a population of approximately 61 million people. Thailand experienced rapid growth in the 1990s, and even at present has a robust economy and growth rate [31]. Thailand does possess considerable amount of NG and a lesser amount of crude oil reserves. Thailand has a very mature and modern energy system, with electrification rate being 99% in 2009 [33]. Thailand is an important economic player in the region, having the second largest economy in Southeast Asia, and accounted for almost 50% of the GDP in the Greater Mekong Sub-region (GMS) [12]. Vietnam is a Southeast Asian country and has experienced rapid economic growth in the last two decades and the GDP growth rate is the best in the region, and second to only India and China [33].

2. Energy situation in Sri Lanka, Thailand and Vietnam

Before analyzing the future energy security of these selected Asian countries and its impact on energy efficiency, it is pertinent

Table 1
Review of literature related to energy security.

Source	Points of interest	Data used and analysis carried out	Critique
Cabalu [9]	Focus on natural gas (NG) supply security. A *four sub-indicator based* composite indicator named gas supply security index to measure gas security was presented. Rationale behind the indicators was presented as well.	Secondary data for 2008 for seven countries and the gas security values were computed. Secondary data has been utilized. Appendix presents the equations of the indicators.	Useful set of indices which were gas intensity, net gas import dependency, ratio of domestic production to total gas consumption and geopolitical risk were presented which may be utilized by scientific community.
Percebois [22]	Energy vulnerability and energy dependence were defined with special impetus on the power sector. Seven points and related equations are presented.	No data based analysis has been carried out. Equations for the relevant types of vulnerabilities identified were given.	The vulnerability indices presented were Import concentration, energy bill, blackout risk, price volatility, exchange rates, industrial factors and technical options. Even though a case study has not been carried out the indices have been explained sufficiently.
Gupta [11]	Oil vulnerability index of oil importing countries was presented. Four sub-indices in the market risk category and three sub-indices in the supply risk category were given.	Data based analysis has been carried out for 26 countries for the year 2004. Data has been obtained from published sources and reports. The computation and relevant equations were given in depth.	In-depth analysis of the oil indices were presented along with case studies. The overall index was divided along the lines of market supply risk. Market risk comprises of oil expense share in GDP, oil intensity, GDP per capita and oil share. Supply risk was broader in nature.
Gnansounou E [10]	The definition and concept of vulnerability were presented. Seven dimensions were determined as being central to reducing the vulnerability of industrialized countries. A composite index was proposed consisting of five sub-indicators.	Case studies have been carried out for six industrialized countries and graphical as well as tabular results presented. The Appendix gives the equations to the computations.	A composite index comprising of energy intensity, oil and gas import dependency, CO_2 emissions per TPES, electricity supply vulnerability, and non-diversity in transport fuels was presented as the energy vulnerability index.
Vivoda V [23]	The focus was on oil import sources and energy security. 12 pertinent factors which affect oil import security have been listed. Five metrics have been cited as involving the 12 factors mentioned.	In terms of quantitative analysis, no primary results have been presented. Rather, already published indices from literature have been presented for three countries.	No explicit indicator has been proposed, but rather qualitative discussion ensues as to why oil import diversity was important and how it affects energy security of oil importing countries.
Vivoda [6]	The focus was on defining ‘‘energy security’’ to be inclusive of many dimensions. In all seven ‘‘energy security’’ dimensions were included. An energy security assessment instrument was also proposed.	Selected indices for 10 Asia Pacific countries were extracted and presented from published sources. The assessment tool presented was also qualitative in nature.	Whilst the paper has offered an alternative way of viewing energy security by not giving quantitative analysis of the method, it left future researchers no clear path.
APERC [4]	Clearly explains the definition of ‘‘energy security’’ and proceeds to give the indices which may be used to evaluate energy security. Five stand alone indicators were presented.	The indicators proposed were used in example calculations to instruct in the method of utilizing the indicators. Case studies were presented for Asia Pacific countries with already published past data.	The indicators proposed were relevant and justified ably in the report. The examples gave a clear and succinct view of how to use the indicators and the interpretations that can be arrived at.
Battacharya [24]	Builds on the vulnerability concept by applying it to selected European countries.	The indicators were adopted from Percebois [22] and past data for the selected European countries were used in computing the indices. The vulnerability was presented in tabular and pictorial form.	The author has gone on to build a scenario for the future and then assess the possible vulnerabilities of the countries. It gave a clear understanding to further researchers as to the accessibility of the indicator.
Grubb et al. [25]	The paper analyzed supply security in the power sector by using two distinct diversity indices; which are Shannon-Weiner Index (SWI) and Herfindahl–Hirschmann Index (HHI)	Both indices have been used to analyze past data of UK electricity generation sector and then also been used for future scenario based analyses.	This paper gave a clear demonstration on the usability and applicability of SWI and HHI indices to measure diversity of an energy system which in turn can be used to indicate energy security.
Loschel et al. [26]	The paper explains the economic aspects of energy security and then goes onto demonstrate with the use of two types of indices, categorized as ex-ante and ex-post.	The paper was illustrated with results using secondary data for industrialized countries. In addition to that a futuristic look was also presented by the authors.	The paper took into account the economic perspective of energy security, hence heavily relying on energy resource price and the economics associated with it.
Chester [2]	The paper defined and clearly explained the term energy security and the characteristics of an energy system that should be taken into account when defining energy security.	The paper presented no outright indicator or any data based analysis. Yet, the paper was very clear and precise in conceptually explaining the nitty-gritties of energy security.	The paper is a seminal and groundbreaking work which gives future researchers the overall view of energy security. Whilst not dealing with quantitative type analysis, it sets apart all the dimensions and principles associated with energy security. The paper can be a foundation for future research.
Jansen et al. [27]	The paper gave a brief overview of different types of energy sources in use in Europe and then goes onto articulate the diversity index as measures of energy security.	It presented the basic diversity indicator based on SWI and then modifies it to include import restrictions, resource based constraints, socio-political stability and resource depletion.	The paper is important in giving a clear description of how the diversity based energy security measure behaves. It provided instructions describing how to actually justify a selection of a measure.
von Hippel et al. [28]	The paper gave a thorough and demonstrative explanation about energy security and the dimensions which should encompass energy security in modern times. Six core dimensions were identified as being core to the concept of energy security and each dimension was then defined by decisively measurable indices.	Any quantitative analysis is not given but it explained how a robust energy security measurement can be carried out.	In terms of substance this paper stands out amongst other literature reviewed thus far. It gave a very succinct yet needful explanation to each dimensions of energy security which are; energy supply, economic conditions, technological criterion,

Table 1 (*continued*)

Source	Points of interest	Data used and analysis carried out	Critique
			environmental criterion, social-cultural and military-security criterion.
Nautilus Institute for security and sustainable development	The report took the conventional approach to energy security by equating it to any security/insurance with the possibility of risk. From there on it tackled energy security at a fundamental level.	As with von Hippel et al. this report also postulated that energy security has six core dimensions and then also described the justification for treating diversity as an important component of energy security.	As far as substance is concerned this report is very qualitative and deals with broad sweeping generalizations. Also, the perspective provided was based on Japan and hence it is very specific to Japan. As part of a learning curve, this report serves the purpose of pushing the boundaries of thinking about energy security.
Kruyt et al. [8]	This paper gave a comprehensive review of the existing security of supply indicators. It also gave the computation of future security of supply for Western Europe using selected indicators.	The past data has been gathered from published sources and the future estimates are based on constructed scenarios. The appendix gives the equations and details of the indicators used	Whilst the paper has offered an example of the analysis that maybe carried out using certain indicators, new and novel concepts have not been espoused in the paper. The analysis presented on the results was noteworthy for future work.
Sovacool et al. [29]	The paper presented a synthesized list of all characteristics and criteria that maybe utilized to evaluate energy security. Five dimensions were given as being core to energy security.	The paper gives qualitative description and has qualitative research as the core of its methodology. An exhaustive list of dimensions, explanations and the indices making up each and every component of the dimension is given in painstaking detail.	A veritable starting point for anyone hoping to understand energy security. The only shortcoming is the lack of inclusion of quantitative reasoning.
Martchamadol and Kumar [30]	This paper presented a comprehensive review of energy security indicators presented in literature and an energy security indicator for Thailand	Thailand's energy security was presented for the years from 1986 to 2009 by using secondary data and then the future energy security was estimated from 2010 to 2030 using three scenarios. Quantitative analyses were presented thoroughly.	The paper clearly gave the justification as to the selection of indicators and presented the equations so as to be a standard bearer in energy security assessment for future researchers.

to analyze the historical levels of energy security experienced by these countries. In this section the historical levels of energy security are measured vis a vis NOID, OS, NGID, GS, NCFS and DOFS, in terms of primary energy supply and power generation.

2.1. Sri Lanka

Sri Lanka and its energy policy are not often discussed in scientific circles. One of the primary reasons is that as a country it is devoid of any non-renewable carbon based fossil fuel resources. Whilst small countries such as Brunei and Kuwait have gained prominence because of the abundance of energy resources they posses, Sri Lanka has gained obscurity due to the lack of it. In the future this may change as last year natural gas was struck in the North East sea basin [34].

Historically, especially since post-independence, Sri Lanka has relied heavily on hydro power to sustain the electricity demand. But in the early 1990s the trend has been to invest in expensive crude oil based thermal power generation plants [35]. This is highly unsustainable and places a huge burden on the already fragile economy of the small country.

In addition to this the government of Sri Lanka has resorted to building the electricity grid by adding coal power plants to the system [36]. In a policy document published in 2006 the government gives the direction it intends to take with regards to the direction and it should be mentioned that the impetus is not on renewable energy systems [32] even though it does pay lip-service to renewable technologies. In addition to this, several reliable media outlets have published that Sri Lanka intends to build nuclear power plants and has aspirations of being a nuclear capable country at least by 2030 [37]. This fact also clearly gives the impression that as a country, the policy impetus on attaining energy security, even though deemed important, is not necessarily through sustainable methods.

In terms of energy management and energy efficiency, the Sri Lanka Sustainable Energy Authority which is under the purview of Ministry of Energy has brought some transparency and accessibility of energy management teaching to the general public [38]. But if Sri Lanka seriously considers the option of energy efficiency then this alone is not sufficient. Another point that needs to be made is that the energy system of Sri Lanka is not mature and sophisticated as some of the other countries in the region. Sri Lanka still uses conventional fuel-wood for domestic purposes and the sophistication of the grid is also placed under severe strain during high demand days. The vagaries of climate change and weather conditions which affect the generating capability of the major hydro systems Sri Lanka is completely at the mercy of oil thermal systems.

Historically, the energy security of Sri Lanka has not been computed or presented in scientific articles. Hence, in this paper the authors review the historic trend of energy security through some relevant indices. Thus, the trend of energy security of Sri Lanka for the past years will be analyzed with the help of OS and NOID, DOFS, and NCFS from year 1990. The historical data for the analysis following in this section is taken from [39] and has been verified with published sources, such as [40]. The analysis of the OS and NOID of Sri Lanka, which are of the same value since Sri Lanka did not possess any oil resources of its own, are given in Fig. 1.

The trend shows that the NOID has grown significantly from being in the middle twenties in 1990 to reach a maximum of over 45% in 2005. This indicates that the energy system of Sri Lanka has become more dependent on oil which is imported. Likewise, the DOFS for both primary energy supply and power generation mix shows an upward trend as in the starting years of the analysis

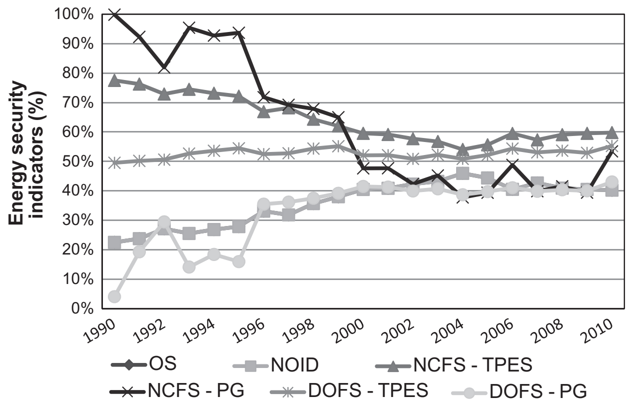

Fig. 1. Historical energy security indicators of Sri Lanka.

Table 2
Sri Lanka energy security indicators and their values in selected years.

Indicator	**1990** (%)	**1995** (%)	**2000** (%)	**2005** (%)	**2010** (%)
OS	22.5	27.9	40.5	44.4	40.2
NOID	22.5	27.9	40.5	44.4	40.2
NCFS–TPES	77.5	72.1	59.5	55.6	59.8
NCFS–PG	99.8	93.7	47.6	39.4	53.4
DOFS–TPES	49.5	54.4	52.1	52.2	55.2
DOFS–PG	4.0	16.0	41.5	39.7	43.0

the Sri Lankan power mix was dominated by hydro power electricity (see Fig. 1)

But it should be understood that whilst the diversification has increased quite sharply in the nineties in lieu of the introduction of oil thermal power plants, the introduction of oil thermal power plants are not entirely sustainable. At the same time, the primary energy supply of Sri Lanka has had almost constant levels of diversification partly due to the dominance of traditional use of biomass, especially in the rural settings of Sri Lanka and the increased use of oil for end use such as transportation.

Fig. 1 also gives the non-carbon fuel share of Sri Lanka for the past years. The trend clearly indicates that Sri Lanka is slowly but surely moving away from non-carbon sources to carbon based fuels such as oil and in the near future, coal. Table 2 gives the raw values of the indicators as calculated by this researcher for the years 1990–2010 in five year intervals which reinforces the results presented in Fig. 1.

The brief analysis presented of the Sri Lankan energy system paints a picture of a small country in the cusp of deciding for one of the two distinct paths ahead of it. Sri Lanka can either choose to go the same way as the trend indicates and get mired down in carbon based, import dependent fuels or it can seriously look to invest in non-carbon based options, of which energy efficiency is a negative-cost option and improve its energy security as well.

2.2. Thailand

Thailand is considered to be a pioneer in terms of energy policy and strategies and the energy situation of Thailand has been reviewed and discussed amongst policy analysts quite often. In contrast to Sri Lanka, energy security of Thailand has been written about in [30] and [41]. Whilst this is not entirely compatible with the research presented in this paper, it is worthwhile to consider the salient points made in those publications. Reference [41] stipulates that energy security of Thailand has not drastically improved, nor drastically declined in the time period of 1990–2010. In fact, according to the interpretation of energy security presented the energy security of Thailand is deemed stagnant.

Thailand implemented a big drive to promote energy efficiency in the electricity consumption sector with the help of supranational institutions such as Global Energy Foundation. It implemented novel funding opportunities for customers and consumers to purchase energy efficient equipment [42]. In addition to this, Thai Ministry of Energy has made a commitment to energy efficiency on a continuing basis with the publication of [43]. Also, in terms of electricity sector, Thailand has in the recent past invested in power import from neighboring countries, mainly Laos and Malaysia. The import of power is also accompanied by Thailand investing in hydropower sources of these countries and purchasing the power produced by these means.

The historical trend of energy security through selected indicators was analyzed. The historic data for Thailand, for the years 1990–2003 have been obtained from [31] whilst data for years 2004–2010 have been obtained from DEDE [44,45].

The indicators presented for Thailand are OS, NOID, GS, NGID, NCFS in power generation (NCFS-PG), NCFS in total primary energy supply (NCFS-TPES), DOFS in power generation (DOFS-PG) and DOFS in total primary energy supply (DOFS-TPES).

Fig. 2 presents the OS and NOID indicator of Thailand and it can be seen that starting from 2007, NOID has been increasing whilst the OS has been declining slightly. This raises the point that Thailand is focused on reducing its oil dependence but due to dwindling domestic resources has to resort to more import of oil resources.

Interestingly NG share has seen an upward trend in the recent past, as NG has replaced oil as a power generation fuel. One can see a direct relation between oil and NG demand in the primary energy sector. Whilst on one hand Thailand has taken measures to reduce the oil demand, it has, as policy opted for NG energy resource, which in the long term will lead to insecurities in the national energy system.

Fig. 2 also shows the DOFS of both primary energy supply and power generation mix of Thailand. The share of non-carbon fuels are low and have shown a declining trend from 1990 onwards, with the introduction of more and more oil and NG into the system. This indicates that the sustainability of Thailand's energy sector is quite poor and more policy measures encouraging the use of non-carbon fuels, such as financial incentives for solar and wind power plants, and availability of biofuels for the necessary sectors should be implemented.

The diversification of the fuel share for the primary energy supply and power generation mix are shown in Fig. 2. Whilst the DOFS of primary energy supply has been held constant in the past and is showing an increasing trend in the near past, the

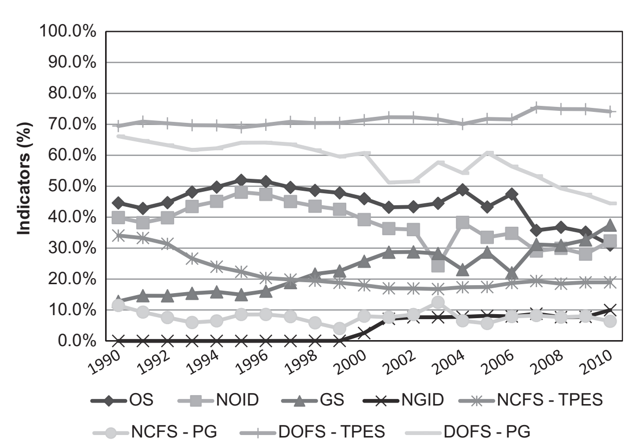

Fig. 2. Historical energy security indicators of Thailand.

diversification of the power mix is declining. The reason for this is that in the recent past more power has been generated with NG. Hence this has lead to the diversification values going down. Table 3 gives the raw values of the indicators for Thailand to reinforce the analysis presented in this section.

The analysis carried out in this section has shown that Thailand has in the recent past contrived to reduce its dependence on oil and thus has increased its dependence on NG, both in terms of primary energy supply and power generation. Another significant fact is that even with so many policy measures in place to encourage renewable energy sources and financial incentives, the non-carbon fuel share of the energy system is remarkably low. This may change in the future as Thailand also has ambitions of commissioning nuclear power plants by 2026 [46].

2.3. Vietnam

Of the three countries analyzed in this study, Vietnam possesses the largest amount of natural energy resources, where it possesses coal, oil and natural gas reserves. As of January 2012, Vietnam is said to possess 4.4 billion barrels of proven oil reserves, ranking it the third in terms of proven oil reserves in the Asia Pacific region behind China and India. Vietnam was a net crude oil exporter until 2010 but Vietnam is a net importer of petroleum products due to limited refining capacity. In 2011 it became a net oil importer [47]. Likewise Vietnam also possesses 24.7 trillion cubic feet of proven NG reserves. In the future Vietnam has the potential to become a significant NG supplier to the region.

After 1986, with the opening up of the economy of Vietnam, the country has seen remarkable growth. Their robust trend is expected to continue into the next decade as well. International organizations such as World Bank and Asian Development Bank and even published sources [48] have reported that the electricity demand of Vietnam has almost quadrupled from 2000 to 2010. In addition, Sovacool [41] has presented certain raw energy data indicators in the analysis of energy security change and trend for Vietnam. It should be pointed out that during the period of 1990–2010 Vietnam marginally improves its energy security according to the analysis presented in [41].

Vietnam has great potential for renewable energy development and government agencies of Vietnam are slowly recognizing and taking steps to utilize more renewable energy technologies. Whilst more foreign direct investment is welcome in Vietnam to invest in renewable energy options developmental agencies are also looking to implement energy efficiency options in the power sector [49].

According to [50] almost a reduction of 12% in the projected electricity demand is possible through energy efficiency measures in the power sector, whilst developing renewable technologies such as hydro power, pumped storage power and wind potential are all theoretically sufficient to supply the electricity demand of Vietnam.

The dichotomy of the global energy problem, that is, the excessive use of wasteful energy on one hand and certain segments of population having no access to clean and safe energy sources on the other is very evident in Vietnam. Whilst the part of the population which has access to electricity utilizes it inefficiently, there is a group of people who have no access to electricity and still depend on traditional solid fuels. The challenge of Vietnam's energy policy makers is to address this dichotomy in a sustainable manner whilst ensuring that energy security of the country is not compromised.

With this background perspective it is pertinent to analyze the historical trend of the energy security indicators. The historical data has been gleaned from [31,51]. Due to data availability issues, the historical analysis has been carried out for a period

Table 3
Thailand energy security indicators and their values in selected years.

Indicators	**1990** (%)	**1995** (%)	**2000** (%)	**2005** (%)	**2010** (%)
OS	44.6	51.9	46.0%	43.3%	31.0%
NOID	39.9	48.1	39.2	33.5	32.3
GS	12.8	15.0	25.7	28.7	37.4
NGID	0.0	0.0	2.5	8.1	10.0
NCFS–TPES	34.1	22.4	18.0	17.4	18.9
NCFS–PG	11.5	8.5	8.0	5.6	6.4
DOFS–TPES	69.4	69.0	71.3	71.8	74.1
DOFS–PG	66.1	64.1	60.7	60.8	44.4

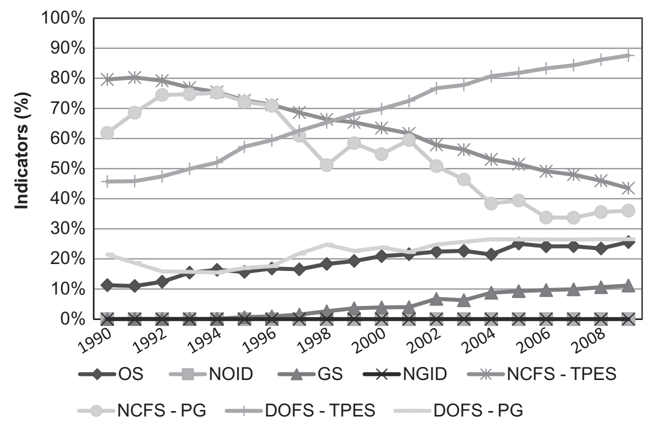

Fig. 3. Historical energy security indicators of Vietnam.

from 1990 to 2009. Reliably published data for the year 2010 is not available for Vietnam.

In terms OS and GS, they have been gradually increasing from 1990 to 2010. This is inevitable since both resources are found in Vietnam. The only caveat is that if energy and power systems are built around these energy resources it becomes hard to convert to other renewable sources. The investment into this energy system becomes a sunk cost and becomes even harder to move away from these fuels and to break the dependence on them (see Fig. 3). The NOID and NGID indicators are moot points in terms of historical analysis as from 1990–2009 Vietnam has been a net exporter of both these energy sources.

As remarked in [47], in 2011 Vietnam became a net oil importer, suggesting that in the near future Vietnam's dependence on oil is going to come at a cost. So unless steps are taken to arrest this dependence on oil, in the long term Vietnam is going to face oil insecurity and gas insecurity at a later date.

The NCFS in primary energy supply and power generation mix is shown in Fig. 3. The NCFS of both primary energy supply and power generation mix are declining which is aided by the fact that Vietnam has not implemented any renewable energy technologies in the time period. In the primary energy supply majority of the non-carbon fuel used is traditional biomass which is debatable in its quality of sustainability. The power generation mix has seen a marked decline from 1990 to 2009, even though in some years in does show an incline. The interpretation is that the Vietnamese power sector is dependent on hydropower and the electricity generated from hydropower is susceptible to change due to adverse weather conditions.

The DOFS of Vietnamese primary energy supply is the only indicator which has shown steady increase since the share of the composition of each fuel type has become more and more equal. The share of oil and NG has increased whilst the biomass share has decreased and this has lead to an increase in diversification. The DOFS-PG has not shown the same level increase as DOFS-

Table 4
Vietnam energy security indicators and their values in selected years.

Indicators	1990 (%)	1995 (%)	2000 (%)	2005 (%)	2009 (%)
OS	11.3	15.7	20.9	25.1	25.6
NOID	0.0	0.0	0.0	0.0	0.0
GS	0.0	0.6	3.9	9.3	11.1
NGID	0.0	0.0	0.0	0.0	0.0
NCFS–TPES	79.6	72.7	63.5	51.5	43.5
NCFS–PG	61.8	72.2	54.8	39.4	36.0
DOFS–TPES	45.7	57.3	69.8	81.8	87.6
DOFS–PG	21.4	16.9	23.8	26.5	26.5

TPES as the reliance on oil and NG has skewed the diversification towards lower levels (see Table 4).

3. Methodology

The methodology adopted is given in the following steps; step 1: collection of the data, step 2: optimization of the energy system using MESSAGE model, step 3: the computation of the results in terms of energy used in all levels, and step 4: analyses of the results in terms of energy security, oil security, gas security and sustainability.

3.1. Data collection

The data needed for this study has been collected from various sources as per each country. In the case of Sri Lanka they have been collected from [39,52,53]. Energy data of Thailand have been collected from [33,46,54] whilst the energy data of Vietnam have been collected from [33,50,51,55]. The energy efficiency measures data of Sri Lanka, Thailand and Vietnam have been collected from [56,57,50], respectively.

3.2. Optimization of MESSAGE

The analysis tool used in this study is the MESSAGE model. MESSAGE is an integer programming based optimization model [58] and has been developed by International Institute of Applied Systems Analysis (IIASA), and currently supported by International Atomic Energy Agency (IAEA). The energy systems of the three countries have been modeled with two scenarios each, namely the reference, and energy efficiency (EE) scenarios. In the reference scenario, the least cost energy options are selected by MESSAGE. The EE scenarios, in addition to the least cost options present in the reference scenario, also contain energy efficiency measures in the demand side sectors: households, commercial and industrial enterprises.

In the Sri Lankan EE scenario the energy efficiency measures in the household sector amount to 2.24 ktoe, 4.48 ktoe and 8.56 ktoe, respectively, in 2007, 2020 and 2030. These energy efficiency measures in the household sector are achieved by savings from efficient lighting, air conditioner and other household appliances at a variable cost of 511.72 USD/toe. The energy efficiency measures in the industry sector amount to 11.45 ktoe, 24.41ktoe and 43.72 ktoe, respectively, in 2007, 2020 and 2030. These energy efficiency measures are achieved by savings through good housekeeping and efficient motors and at a variable cost of 174.45 USD/toe. The energy efficiency measures in the commercial sector amount to 19.08 ktoe, 40.69 ktoe and 72.88 ktoe, respectively, in 2007, 2020 and 2030. These measures are achieved by energy savings in commercial buildings and the electrical appliances in them, at a variable cost of 209.34 USD/toe. These data have been extracted from [59]. In the Thai EE scenario, energy efficiency savings in the household sector amount to 110.08 ktoe, 142.4 ktoe and 173.6 ktoe, respectively, in 2007, 2020 and 2030. These savings are achieved by energy efficiency improvement in electrical appliances in homes. In the same way, energy efficiency savings in the industry sector are 19.35 ktoe, 30.26 ktoe and 42.69 ktoe, respectively, in 2007, 2020 and 2030. The majority of these savings are achieved by improvements in the motor efficiency and also by the improvement in the electrical appliances used in the industry. The energy efficiency measures in the commercial sector amount to 15.48 ktoe, 24.21 ktoe and 34.15 ktoe in 200, 2020 and 2030, respectively. These measures are achieved by energy efficiency improvement in commercial buildings at a variable cost of 8 USD/MWh. These data have been extracted from [57]. In the EE scenario of Vietnam, household energy efficiency savings amount to 101.01 ktoe, 486 ktoe and 812 ktoe in 2007, 2020 and 2030, respectively. These savings are achieved by an effort to improve energy efficiency levels of household electrical appliances at a variable cost of 189.57 USD/toe. Likewise, the energy efficiency measures in the industry sector amount to 138 ktoe, 590 ktoe and 1161 ktoe in 2007, 2020 and 2030, respectively. These measures have been achieved at a cost of 127.93 USD/toe. In the commercial sector of Vietnam the energy savings amount to 19 ktoe, 51 ktoe and 92 ktoe, respectively, at a variable cost of 93.04 USD/toe. These data for the EE scenario of Vietnam have been extracted from [50].

The case studies are modeled for the time horizon from 2007 to 2030, with the base year in 2007. The emission factors of power generation have been obtained from [60].

3.3. Energy security

This paper analyses energy security along three themes which are oil security, gas security and sustainability. Each theme consists of five sub-indicators which assess the themes respectively. All sub-indicators have been given on a scale of 0–100, where 0 indicates minimum security and 100 indicates maximum security.

3.3.1. Oil security

Oil security consists of five sub-indicators which are oil supply risk indicator (OSRI), oil import intensity (OII), oil intensity (OI), oil share (OS) and net oil import dependency (NOID). These sub-indicators have been adopted from [4,11]. The sub-indicators of OSRI, OS and NOID are naturally calculated to be percentages, but OI and OII are obtained as raw values. These values are then normalized according to the method prescribed by Cabalu [9]. Oil security is then computed as the mean average of the five sub-indicators.

3.3.2. Gas security

The gas security sub-indicators follow the oil security sub-indicators closely and they are gas supply risk indicator (GSRI), gas import intensity (GII), gas intensity (GI), gas share (GS) and net gas import dependency (NGID). These sub-indicators have been adopted from Ref. [9]. Gas security is then computed as the mean average of the five sub-indicators.

3.3.3. Sustainability

The sustainability theme also consists of five sub-indicators which are Diversity of Fuel Shares (DOFS), non-carbon fuel shares (NCFS), renewable fuel shares (RFS), carbon emission intensity (CEInt) and carbon emission per capita (CECap). These sub-indicators have been adopted from Ref. [61]. Sustainability is then computed as the mean average of the five sub-indicators.

4. Results

The results are to be presented in terms of energy security and the individual sub categories which make up energy security according to this paper, which are oil security, gas security and sustainability.

4.1. Energy security

The results of energy security of the three countries are presented in Fig. 4. Fig. 4 shows the energy security values for the three countries in 2007, 2020 and 2030. In the case of Sri Lanka there is clear indication as to the positive effect of energy efficiency improvements by the significant increase in the energy security level between the reference and the EE scenarios. This gives reason to believe that Sri Lankan energy security will benefit moderately by implementing energy efficiency improvement measures in the demand side. Another trend to be noticed in the case of Sri Lanka is that in both the references and the EE scenarios energy security increases to the maximum value in 2020 but then reduces gradually to a value of approximately 40% and 53% in the reference and the EE scenarios respectively. The reason for this is that in the medium term of Sri Lanka implementing energy efficiency improvements has a discernible effect on improving energy security. But in the longer term, with an increasing energy system, the effect of the same energy efficiency improvement decreases significantly.

In the case of Thailand, which has a more mature and the biggest energy system of the three countries, the trend in energy security in the progressive years suggest that focusing only on the energy efficiency improvements is not going to be sufficient for Thailand to improve energy security. There is a progressive decrease in energy security in both scenarios, and in the final year the energy security levels converge.

Vietnam, as mentioned in Section 2.3, possesses considerable amount of natural resources in oil and NG. The energy efficiency improvements do not have a drastic effect on Vietnam's energy security due to this fact. As shown in Fig. 4, there is only slight increase of energy security in the EE scenario in comparison to the reference scenario. Again, this can be explained by the fact that if a country possesses oil and gas, the energy security is not going to see an enhancement because of energy efficiency improvement in the demand side.

One of the common trends to be noticed in all three countries is that energy security gradually decreases after the year 2020. In fact this trend leads to surmise that in the longer term future improving energy security should not be dependent only on one action such as energy efficiency improvement, but rather be with a help of multitude of actions, such as changing the fuel composition of generation mix of power plants, fuel mix in the transport sector etc.

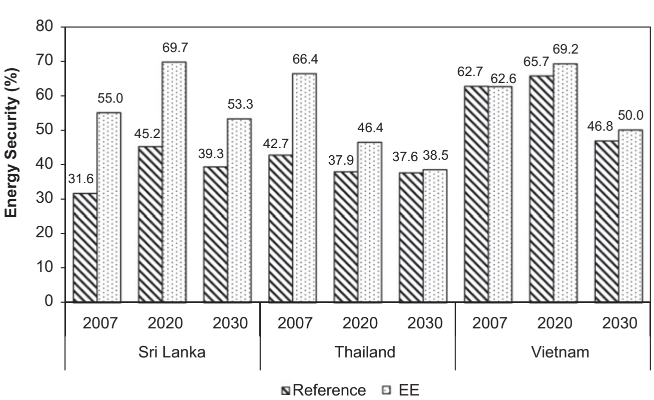

Fig. 4. Energy security of Sri Lanka, Thailand and Vietnam in selected years.

The results also suggest that it is futile to focus on energy security improvement of developing countries by solely depending on energy efficiency improvements, even though there is significant improvement in the short and medium terms.

4.2. Oil security

The oil security of the three countries in 2007, 2020 and 2030 are given for the two scenarios in Fig. 5. Sri Lankan oil security shows considerable improvement in the EE scenario as compared to the reference scenario, especially in 2007. This is due to the fact that at present oil is extensively used for power generation in Sri Lanka and it has to be imported as Sri Lanka does not possess any oil resources. But as the years progress in the reference scenario, oil security will gradually improve, as less expensive energy options are chosen in comparison to oil thermal options, such as renewable and coal power plants. It shows gradual improvement in the levels of oil security in the reference scenario. As for the EE scenario, once a maximum oil security of around 60% has been reached, the oil security remains more or less constant at that level. This is because, inherent to the Sri Lankan oil demand, this is the maximum security attainable as oil in Sri Lanka is also used in other sectors such as in the transport sector. But it should be noted that the improvement of oil security in the EE scenario, even in the latter years, in comparison to the reference scenario are significantly higher which shows that pursuing the EE scenario is a possible way of increasing oil security of Sri Lanka. The gap between the reference and the EE scenarios reduces as the year progresses from 2007 to 2030.

The oil security of Thailand, given in Fig. 5 shows that in the reference scenario, it is almost constant throughout 2007–2030 at a level of approximately 45%. This is consistent with the aim of planning policies of Thailand which is to hold the oil security at a constant level without any fluctuations. In the case of EE scenario, the oil security is highest in 2007, but in the middle of the study period the oil security declines sharply. The reason for this is the fact, in the EE scenario, oil resources Thailand possesses are chosen until it is fully exploited and hence once the oil resources are depleted the oil security will sharply decrease. Once the lowest oil security value has been reached, it shows a gradual increase and in the last year oil security values of both scenarios are the same.

The oil security of Vietnam does not show any significant improvement between the reference and the EE scenarios, and the main reason for this is the availability of oil resource in Vietnam. Till 2020, the Vietnam's oil resource is sufficient to meet the demand, and with the building of refineries in 2009 and 2012 the need to import refined oil also ceases. Hence we see the gradual increase in oil security from 2007 to 2020 in both scenarios. Then in 2020, according to the modeling parameters, Vietnam would deplete its oil resources and hence will need to start importing oil again and hence we see the decline in oil security in both scenarios from 2020 to 2030. Because of the availability of national oil resources the energy efficiency measures in the demand side do not have the impact which is to be expected generally.

4.3. Gas security

Gas security of Thailand and Vietnam for the years 2007, 2020 and 2030 are given in Fig. 6. It is worth noting that Sri Lanka does not utilize NG and hence the gas security of Sri Lanka has not been computed or accounted for in this paper.

The gas security of Thailand is considerably improved in 2007, from the reference to the EE scenario, which is expected as the main fuel utilized for electricity generation is NG in Thailand

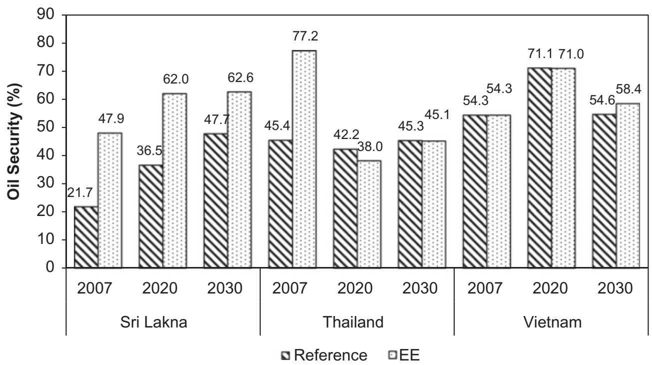

Fig. 5. Oil security of Sri Lanka, Thailand and Vietnam in selected years.

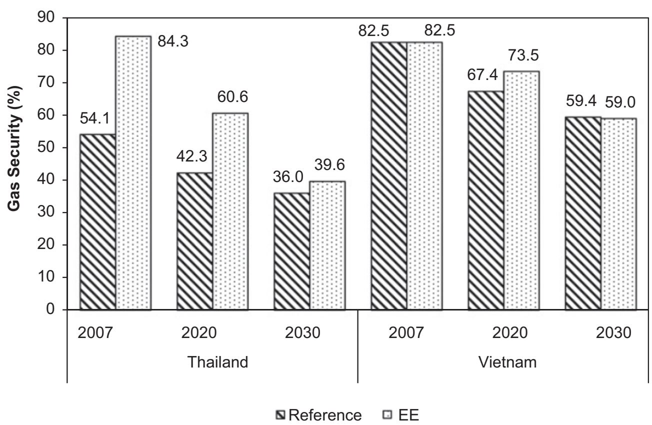

Fig. 6. Gas security of Thailand and Vietnam in selected years.

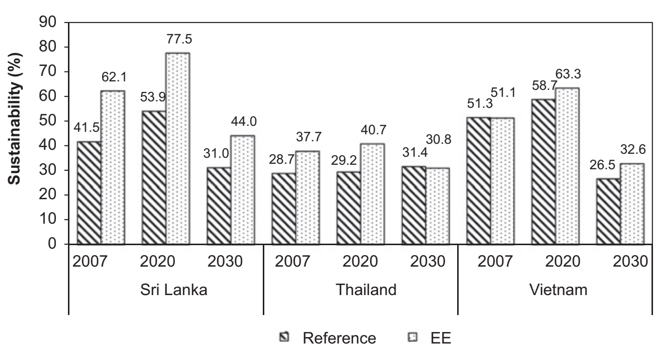

Fig. 7. Sustainability results of Sri Lanka, Thailand and Vietnam in selected years.

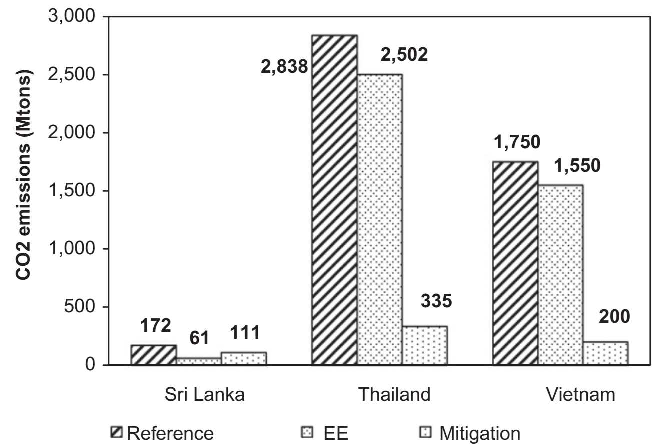

Fig. 8. Comparison of CO_2 emissions in the reference and the EE scenarios.

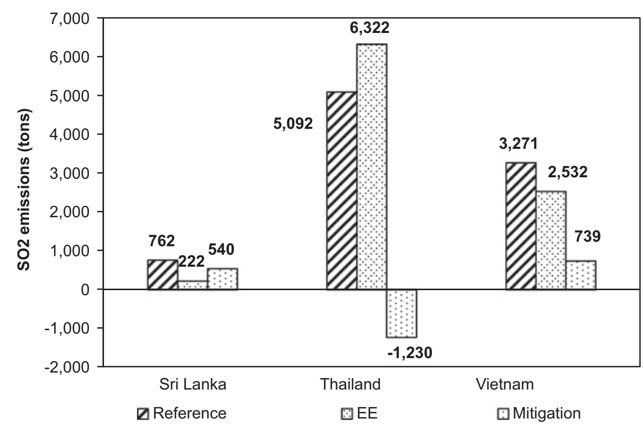

Fig. 9. Comparison of SO_2 emissions in the reference and the EE scenarios.

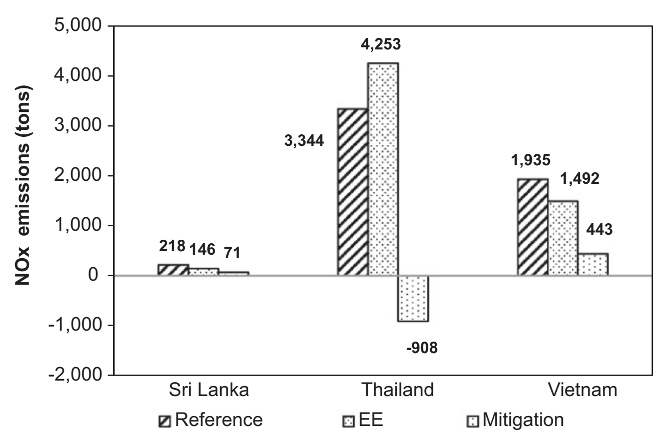

Fig. 10. Comparison of NO_x emissions in the reference and the EE scenarios.

(see Section 4.5.3, Fig. 12a and b). The gas security in the EE scenario also gradually reduces to be equal to that of the level of gas security in the reference scenario. The reason for this is that in the long term, with an ever burgeoning energy system, mere energy efficiency improvements are not sufficient to help improving gas security.

The gas security of Vietnam as seen in Fig. 6 does not show any considerable improvement between the two scenarios, which is understandable as Vietnam possesses its own NG which implies that Vietnam does not import NG. But with a burgeoning demand in terms of electricity, reliance on the Vietnamese power generation on NG increases considerably from 2007 to 2020 which in turn results in the improvement in the gas security in the EE scenario in 2020. After 2020 even increasing dependence on imported NG sees the gas security values of both scenarios converge.

In terms of both Thailand and Vietnam, it can be concluded that there is significant potential in improving the gas security of both countries by energy efficiency improvement measures as both countries depend on NG in electricity generation, but as with energy security and oil security in the long term, developing countries would have to look towards a basket of policies and measures to improve gas security, rather than just depend on one course of action.

4.4. Sustainability

The sustainability results of the three countries are given in Fig. 7.

Sustainability of Sri Lanka for both the reference and EE scenarios are shown in Fig. 4. The behavior exhibited by the sustainability theme is dissimilar to that of oil security of Sri Lanka. Sustainability in the reference scenario is at a lower level and then gradually increases to attain a maximum in 2020 and then starts declining from them on to a value of approximately 44%. The reason for this is the introduction of coal power plants as planned by the Government of Sri Lanka in 2023. This plan significantly reduces the sustainability of the system by considerable amount of emissions of CO_2, whilst also reducing the non-carbon fuel share in the energy system. The same trend is also exhibited in the EE scenario, but the significant factor to be noted is the increase in sustainability of the EE scenario in comparison to the reference scenario. The improvement is approximately 30% which is very significant and which in turn will enhance the energy security of Sri Lanka. The reason for the increase in sustainability is the energy efficiency measures which are modeled as supply side options which in turn lead to the delay of the use of coal power plants for electricity generation.

In the case of Thailand, sustainability in the reference scenario is almost constant at a level of 30%, which implies that status quo is at a perennially low level if no intervention is taken. Whilst there is improvement in the EE scenario in comparison to the reference scenario the improvement in the short term period of 2007–2020, as with energy security, the sustainability of the energy system converges to the same value in the reference scenario. Again this indicates that in the long term, Thailand should look towards a lot more measures to improve the sustainability of its energy system.

Vietnam faces a rapid decline in the sustainability of its energy system in the reference scenario from 2020 to 2030, which is understandable as the ever increasing demand of the country will mean that Vietnam has to increase its coal power plants, which in turn are set to emit CO_2 and reduce the share of non-carbon and renewable fuel share in the generation mix. This implies that the highest parity between the reference and the EE scenarios in 2030, which is understandable as the electricity generation averted due to the energy efficiency measures increases the sustainability values.

So it may be concluded that Sri Lanka and Vietnam show palpable improvement in sustainability due to the energy efficiency measures, whilst Thailand shows improvement only in the short term, but in the long term the less improvement there is.

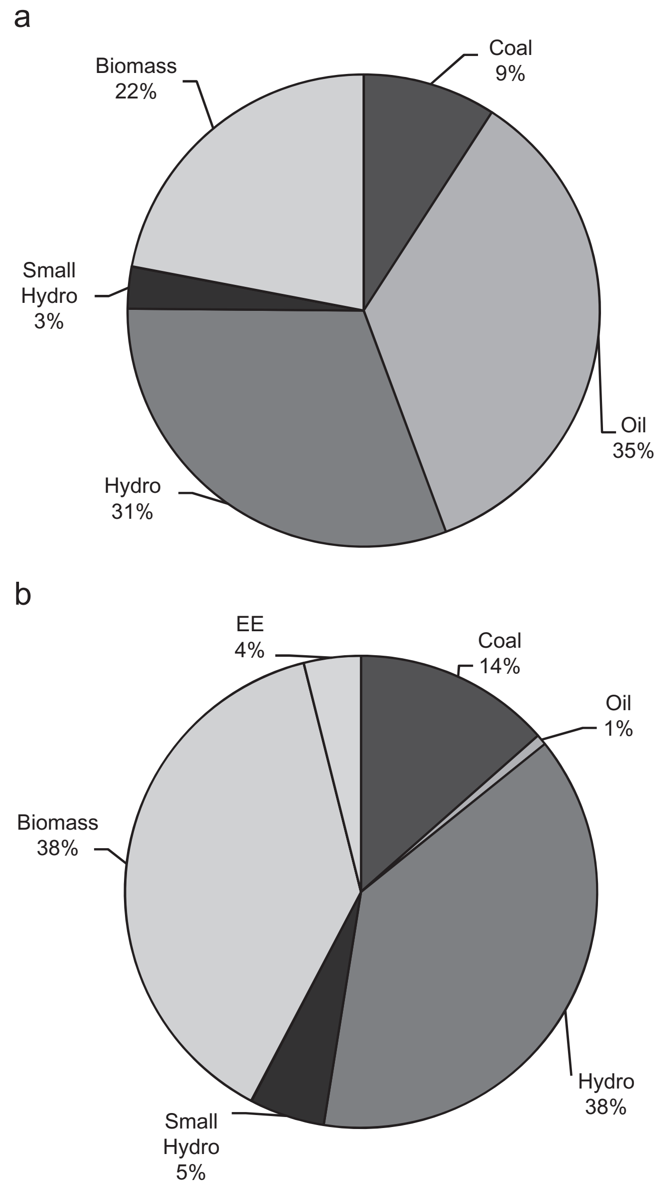

Fig. 11. (a) Electricity generation mix of Sri Lanka in the reference scenario (b) Electricity generation mix of Sri Lanka in the EE scenario.

4.5. Co-benefits of energy efficiency improvements

The co-benefits are analyzed in terms of CO_2 emissions, local air pollutants SO_2 and NO_x emissions and the conventional primary energy use.

4.5.1. CO_2 mitigation

The total CO_2 emissions of Sri Lanka, Thailand and Vietnam in the reference and EE scenarios and the mitigation in the EE scenario are presented in Fig. 8.

Fig. 8 shows the CO_2 emissions in the three countries for the time horizon of 2007–2030 in the two scenarios and the total mitigation in the EE scenario in the same period. In the case of Sri Lanka, there is significant mitigation of CO_2 due to the EE scenario and the energy efficiency measures implemented. The energy efficiency measures postpone the requirement of a coal power plant which is otherwise selected and commissioned in 2015 in the reference scenario, which lead to the very high mitigation, approximately 111 million tons of CO_2. In the cases of Thailand and Vietnam whilst the mitigation is significant, it is not as high as in Sri Lanka. The primary reason for this might be the fact that electricity generation in both countries is dependent on natural gas and oil, rather than coal in the short term. In the reference scenario, where the status quo is maintained, both Thailand and Vietnam utilize their already existing power plants and the majority of which are natural gas based combined cycle plants. But in the EE scenario no such constraint is applied on the model and the model is free to choose the least cost option and hence it chooses coal power plants. Even though energy efficiency measures have effects on CO_2 emissions, the mitigation effect reduces as the MESSAGE chooses power plants based on the least cost option, which implies in the long term it chooses coal power plants. But even with this, it should be noted the CO_2 mitigation is an important and viable co-benefit of energy efficiency measures.

4.5.2. Local air pollution mitigation

The local air pollution mitigation is analyzed with regards to the emissions of the SO_2 and NO_x gases in the reference and EE scenarios of the three countries. The emission factors are obtained from Ref. [38].

Results in Figs. 9 and 10 present the emissions and mitigation of SO_2 and NO_x, respectively. Results presented in terms of SO_2

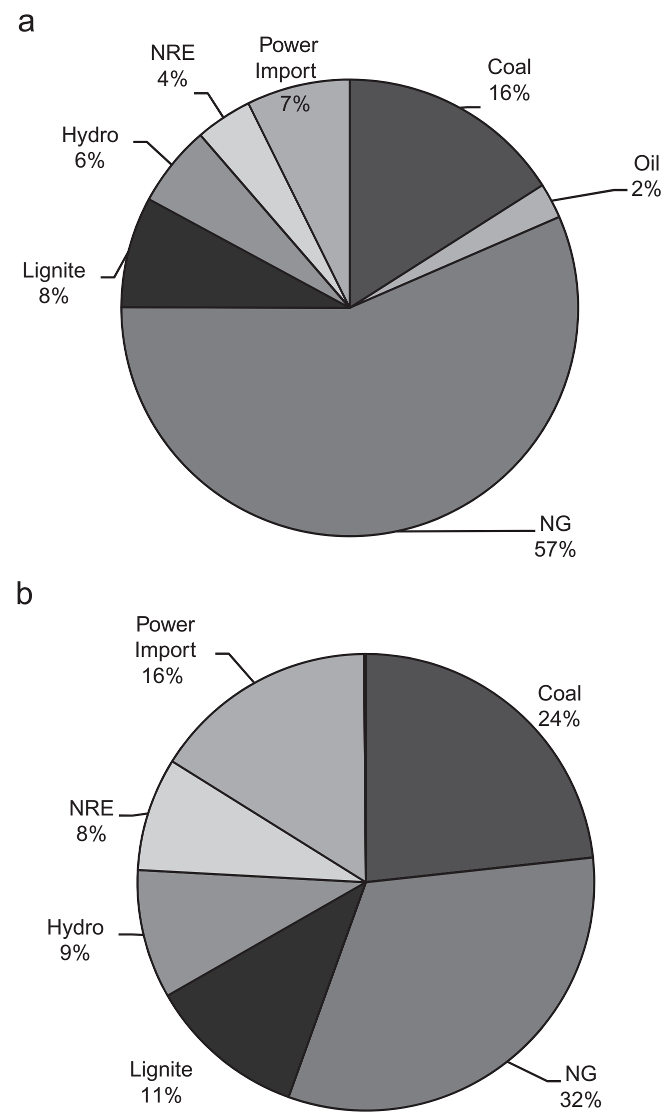

Fig. 12. (a) Electricity generation mix of Thailand in the reference scenario (b) Electricity generation mix of Thailand in the EE scenario.

and NO_x should be analyzed and interpreted in conjunction with the total electricity generation mix of the three countries. Thus Figs. 11a, 12a, and 13a present the total generation mix of Sri Lanka, Thailand and Vietnam in the reference scenario, respectively and Figs. 11b, 12b, and 13b present the total generation mix of Sri Lanka, Thailand and Vietnam in the EE scenario, respectively. It is worth to be noted that in the case of Thailand in Fig. 12a and b, lignite is considered as a separate generation option as lignite is a domestic resource and other coal used in power generation is imported. This distinction has been made whilst the case study of Thailand was modeled as well.

Whilst the total mitigation resulting in the EE scenario is positive and beneficial in Vietnam and Sri Lanka, it can be seen that the SO_2 and NO_x emissions increase in Thailand. This is because of the selection of coal power plants in the EE scenario, where coal has the highest emission factor of SO_2 and NO_x. In the power generation mix of Thailand, as depicted in Fig. 11a and b, the participation of coal increases from 16% in the reference scenario to 24% in the EE scenario. Another important aspect to be noted is that the share of EE measures is so negligible that it is almost equal to zero. Whilst a considerable amount of generation is avoided as a result of energy efficiency measures, once the maximum energy efficiency practically possible is implemented, the model chooses the least cost generation option which is coal powered generation regardless of the nature of the power system. This in turn leads to the high emissions of SO_2 and NO_x in Thailand, where EE measures listed as supply side options are not fully utilized and coal is selected to replace some of the gas power generation use. Due to the sheer size of the power sector of Thailand, the reduction is achieved by the energy efficiency measures is up-ended by the new coal power plants in the long term (2020–2030). In the case of Vietnam there is no considerable change in the generation mix from the reference and EE scenarios (see Fig. 13a and b). This is understandable as Vietnam possesses considerable amounts of natural resources in terms of oil and NG. Sri Lankan generation mix shows considerable change, where EE measures has a 4% contribution in the generation mix, but regardless of this the contribution of coal also increases from 9% in the reference scenario to 14% in the EE scenario (see Fig. 11a and b). This might have lead to the increase in SO_2 and NO_x emissions, but the emissions of these were mitigated because of the unprecedented reduction in the use of oil (from 35% in the reference scenario to just 1% in the EE scenario). The significant

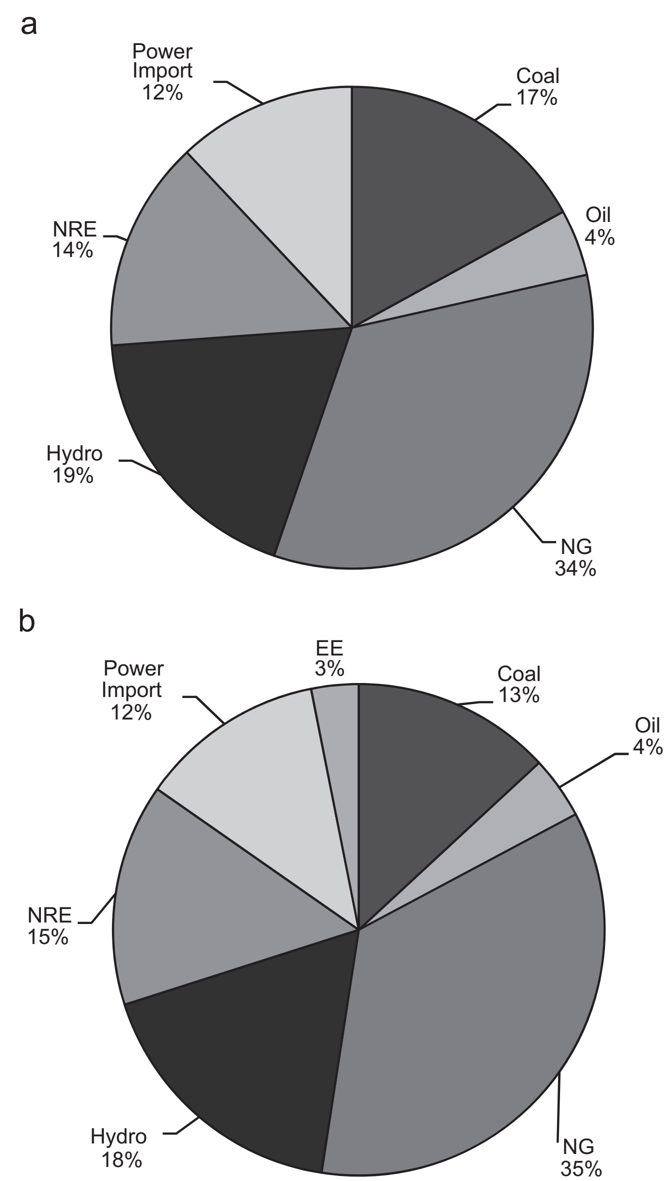

Fig. 13. (a) Electricity generation mix of Vietnam in the reference scenario (b) Electricity generation mix of Vietnam in the EE scenario.

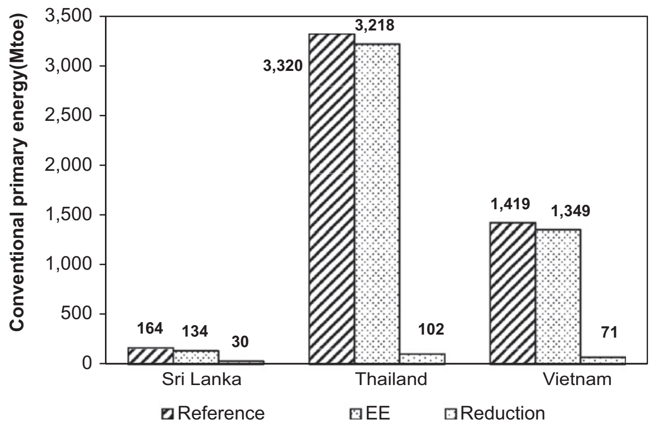

Fig. 14. Total conventional primary energy in the reference and the EE scenarios.

reduction offset whatever increase might have resulted due to the spike in coal use in the generation mix.

4.5.3. Conventional primary energy use

This subsection deals with the reduction of conventional primary energy use in the two scenarios and the effect of energy efficiency measures on the conventional primary energy use. In this study conventional primary energy comprises of coal, oil and NG. Fig. 14 shows results of the conventional primary energy use in the three countries. Results suggest that there is conceivable and significant amount of reduction of the conventional primary energy used in the EE scenario in comparison to the reference scenario in all three countries. The conventional primary energy resources are avoided because of savings in energy efficiency measures, which in turn reduce the need for conventional primary energy, such as in the case of Sri Lanka, the need for oil to generate electricity.

5. Conclusions

It can be concluded that energy security is increased considerably with energy efficiency measures in Sri Lanka and increased to a smaller level in the case of Thailand and Vietnam. Sri Lanka shows an increase of approximately 30% in energy security in 2007 in the EE scenario in comparison to the reference scenario. The EE scenario still shows an increased energy security level in 2030. Even though both scenarios in Vietnam have the same energy security in 2007, as times progress the EE scenario has a better energy security than the reference scenario. In the case of Thailand in 2007 energy security in the EE scenario is approximately 20% better than the reference scenario, but as the years progress the energy security level of both scenarios converge on to the same value. The reason for there not being considerable improvement in the latter years in Thailand and Vietnam is that both have large and to a certain extent diverse generation mix and as the years progress the energy efficiency measures are not enough to have significant beneficial impacts. Rather, these countries should implement energy efficiency measures in terms of carbon intensive and imported fuels, and also convert to domestically produced fuels. It should also be noted that co-benefits of energy efficiency in all three countries are significant. The total CO_2 mitigation is 111 Mtons, 335 Mtons, and 200 Mtons of CO_2 for Sri Lanka, Thailand and Vietnam, respectively. The total reduction of conventional primary energy use is 30 Mtoe, 102 Mtoe and 71 Mtoe for Sri Lanka, Thailand and Vietnam, respectively. In terms of total mitigation of SO_2 and NO_x gases for the time period of 2007–2030, Sri Lanka shows a total mitigation of 540 t and 71 t respectively whilst in Vietnam it amounts to 739 t and 443 t of SO_2 and NO_x, respectively. Thailand shows an increase in both SO_2 and NO_x emissions due to the high amount of proliferation of coal power plants in the latter part of the modeling horizon. The increase for 2007–2030 is 1230 t and 908 t of CO_2 and NO_x, respectively.

Acknowledgments

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